A PRELIMINARY INVESTIGATION OF ACOUSTIC ENERGY TRANSMISSION FROM A TAPERED FLUID LAYER INTO A FAST BOTTOM

James Nathaniel Edwards

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THESIS

A PRELIMINARY INVESTIGATION
OF ACOUSTIC ENERGY TRANSMISSION
FROM A TAPERED FLUID LAYER
INTO A FAST BOTTOM

by

James Nathaniel Edwards, Jr.

December 1976

Thesis Advisor: A.B. Coppens

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The transmission of acoustic energy from a tapered fluid layer into an underlying layer of fluid was investigated. Pulsed transmissions at frequencies of 75.85 kHz and 107.5 kHz were used to insonify the upper layer while a small probe transducer was used to measure signal amplitude variation with depth in the lower layer. The experimental data collected indicate that a directional transmission of acoustical energy into the lower layer occurs over regions corresponding to the individual cutoff depths for normal modes in the upper layer. A simple method for estimating the position of these regions is discussed and the effects of frequency and upper layer slope variations are reported.

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I. INTRODUCTION

The propagation of sound in shallow water has been the subject of considerable theoretical and experimental research beginning with the study of propagation in layered liquids by C. L. Pekeris [Ref. 1]. In the Pekeris problem a point source and point receiver are positioned in a non-absorbing fluid layer of constant depth which overlies a semi-infinite layer of fluid having higher sound speed and density. The dominant portion of the solution posed by Pekeris is a summation of normal mode contributions with cylindrical spreading losses. Numerous studies of acoustic propagation in two-layered fluid models have subsequently been conducted to verify or improve upon the Pekeris solution. One example of such research is the experimental work reported by Knudsen [Ref. 2] which demonstrated that the theory generally predicated the observed behavior within experimental error.

When the depth of the top layer of fluid is not constant, the Pekeris solution is no longer valid and the problem becomes considerably more complex. Williams and Lewis [Ref. 3] posed a solution which postulates that the normal modes adjust themselves adiabatically to the local depth when the depth varies slowly. This hypothesis was subsequently supported by the results of experimental work reported by Eby, Williams, Ryan, and Tamarkin [Ref. 4].

As described in Ref. 5 and elsewhere, each normal mode may be thought of as a pair of plane waves propagating in a duct or waveguide by successive reflections at the boundaries. These plane waves are incident upon the boundaries at an angle which is determined by the characteristic propagation vector of the corresponding mode. If the angle of incidence is greater than the critical angle for the given boundaries, propagation with relatively low attenuation will occur because virtually all of the acoustic energy is reflected. When the angle of incidence is equal to the critical angle, transmission of energy across the boundary begins and the corresponding mode is said to have reached cutoff. In the classic two-layered fluid problem with constant geometry, the directions of the mode propagation vectors (and thus the angle of incidence) vary with the transmission frequency. It is therefore possible to define a cutoff frequency for the nth mode which is given by Knudsen [Ref. 1] and others as follows:

$$f_n = \frac{(2n-1)}{4h} \frac{c_1}{\sqrt{1-(c_1/c_2)^2}} , \quad n=1,2,3,\ldots$$

where h = depth of the upper layer

c_1 = sound speed in the upper layer

c_2 = sound speed in the lower layer.

This means that at frequencies less than f_n, the nth and higher numbered modes are evanescent.

The foregoing equation can also be solved for a cutoff depth, h_n, by rearranging variables and holding the frequency constant. This yields the minimum upper layer depth required to allow propagation in the nth and lower numbered modes. Based upon the observations reported in Ref. 4, this cutoff depth concept may be extended to deal with the problem of propagation in a slowly tapered upper fluid layer as suggested in Fig. 1. When the geometry of the tapered layer and the sound speed in both layers are known, it should be possible to predict, with reasonable accuracy, the regions in which significant transmission of acoustic energy into the lower layer occurs.

The optical analog of the foregoing concept has been verified in an experiment reported by Tien and Martin [Ref. 6]. The waveguide in their experiment was formed by depositing a thin dielectric film with a tapered edge on a substrate having a higher refractive index. A light beam from a laser was coupled into the film and subsequent transmission into the substrate was observed. The transmission of light energy into the substrate commenced at a distance of several optical wavelengths in front of the cutoff region and was concentrated in a beam projected at an angle of 15 degrees below the film-substrate interface.

The primary objectives of the experimental research reported herein are as follows:

1. To verify that the transmission of significant acoustical energy into the lower layer of a two-fluid, tapered waveguide is confined to well-defined regions corresponding

to the points at which the modal cutoff depths are reached in the upper layer.

2. To determine whether or not the transmissions observed in these regions create a beam-shaped acoustical field in the lower layer.

3. To determine some of the major effects produced by separately varying the transmission frequency and the slope of the upper layer taper.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

A. APPARATUS

The experiment reported herein was performed in a specially constructed plywood tank at the Naval Postgraduate School. The tank was fabricated from 3/4-inch plywood with all interior surfaces heavily coated with Varathane (TM) liquid plastic to provide watertight integrity. The upper edge of the tank was rimmed with 2x4-inch stock and the sides were reinforced with 3/4-inch plywood struts to provide rigidity.

The determination of the shape and dimensions of the tank was subject to several considerations. Initial research indicated that the procurement of the desired fluids would be the major cost factor in this experiment. It was therefore decided to reduce the volume of fluids required by using a wedge-shaped tank rather than a conventional rectangular design. A second benefit of the wedge shape was that it helped to reduce interference due to acoustic reflection from the sidewalls of the tank. The length of the tank was chosen to accommodate the use of a tapered upper fluid layer with slopes varying from 0.02 to 0.05 over a minimum distance of one meter. The depth of the tank was chosen to provide for a lower fluid layer of at least 40 cm so that it could be considered semi-infinite for pulsed transmission. The basic features of the tank are depicted in Fig. 2a.

In the typical shallow water problem the sloping bottom gives the water layer above it a tapered shape and the water's upper surface forms a level, pressure-release boundary. In a two-fluid model it is impossible to slope the bottom layer of fluid without separating the fluids with a rigid intermediate layer of glass or similar material. The top surface of the upper layer was therefore sloped by using a reinforced sheet of 3/4-inch plywood covered with foam-filled neoprene wetsuit material 1/8-inch thick. At the frequencies of interest, it closely approximates a pressure-release surface. A framework of aluminum angle beams was mounted on top of the tank and accurately leveled. The neoprene-covered board was then suspended from this framework and could be accurately positioned at the desired depths and angles.

The acoustic source was constructed from a rectangular bar of barium titanate with the following dimensions; length = 2.7 cm., width = 0.9 cm., thickness = 1.28 cm.. Biased for resonance in its thickness mode, this source had a measured beamwidth of approximately 180 degrees in the vertical direction and 70 degrees in the horizontal direction at a frequency of 75.85 kHz. A number of frequencies were usable in the range from 75 to 200 kHz. The signal to noise ratio at these frequencies was sufficient to avoid amplification and filtering difficulties.

The receiver, a standard LC5-2 probe transducer manufactured by CELESCO Industries, has a lead zirconate element

with a diameter of 0.093 inch mounted on the tip of a tapered stainless steel tube. The acoustic center of the element is located 0.125 inch from the tip of the probe. The transducer was mounted vertically in a 3/8-inch stainless steel tube bent at right angles to reach down the side of the tank and project outward toward its center. A pointer was positioned directly above the tip of the transducer by means of an aluminum rod attached to the steel tube as depicted in Fig. 2b. The transducer mechanism was then attached to a carriage which slid on level rails mounted above the edge of the tank. This system allowed the transducer to be positioned vertically with an accuracy of plus or minus one millimeter. The same accuracy was achieved in positioning the transducer horizontally along the centerline of the tank. All measurements were made using the aluminum framework previously described as a reference.

The source transducer was driven by the amplified output of a Wavetek Model 116 voltage-controlled generator which was triggered by a General Radio Model 1310-B oscillator. The received signal was amplified by a factor of 40 dB and displayed on a multiple-beam oscilloscope. No filtering was necessary to maintain adequate signal to noise ratios.

The lower fluid layer was a heavy brine with a depth of 43.5 cm. The brine was produced by mixing 100 lbs of sodium chloride (NaCl) and 150 lbs of calcium chloride ($caCl_2 \cdot 2H_2O$) in approximately 120 gallons of tap water. The

resultant solution had a density of 1170 kg/m^3 and a sound speed of 1740 m/sec at 23 °C. Olive oil was used to form an upper fluid layer with a maximum thickness of 4.0 cm (after the sloping board was positioned in the tank). Olive oil was chosen because it would not deteriorate the neoprene covering on the board and had relatively low density and sound speed: 905 kg/m^3 and 1425 m/sec, respectively.

B. PROCEDURE

The neoprene-covered board was positioned at an initial angle of 2.28 degrees relative to the surface of the brine layer and intersecting that surface at a distance of 28 cm from the wide end of the tank. (Refer to Fig. 3.) This formed a tapered duct in the upper layer with an initial depth of 4.0 cm and a length of 100.4 cm. The source transducer was positioned at the narrow end of the tank with its vertical axis on the tank centerline and its horizontal axis at a depth of 2.0 cm in the upper layer. The distance from the face of the transducer to the beginning of the tapered section was 23.5 cm.

The general experimental procedure was very straightforward. The source was excited with a tone burst at a repetition rate of 100 cycles per second and pulse durations of approximately 100 microseconds. The probe transducer was then moved systematically to obtain the acoustic signal amplitude at selected depths and distances along the centerline of the tank. The pertinent components of the

received signal were identified by their variation with a combination of source and receiver movement when necessary. Horizontal distance measurements were referenced to the point at which the tapered section of the upper layer terminated (i.e., upper layer thickness equal to zero). The positive direction is taken when moving toward the source (upper layer thickness increasing). Vertical distance measurements were referenced to the fluid-fluid interface with the positive direction upward.

III. RESULTS

A. GENERAL OBSERVATIONS AND REMARKS

The received signal was too complex to allow adequate resolution of its components when frequencies above 120 KHz were used. The vertical and horizontal beamwidths of the source transducer were considerably wider at the lower ferquencies ultimately utilized, but it was possible to identify the components of the received signal. Components of the signal related to paths involving single reflections from the sides of the tank, had arrival times that averaged 0.06 msec later than the direct path arrival time. This was confirmed by computing multipath arrival times based on the geometry of the model. The relative amplitude of the side-reflected component was larger at positions corresponding to large source-receiver separations. The directionality of the source caused the reflected component to be relatively insignificant at shorter separation distances. The higher sound speed in the lower fluid layer allowed signal components related to a single bottom bounce path to arrive as much as 0.6 msec earlier than the direct path component. The relative amplitude of this component was, however, considerably less than that of the side-reflected component due to the longer path it traversed and to transmission losses at the fluid-fluid interface. Considerable care was taken throughout the experiment to reduce the effects of multipath interference by measuring the received pulse at a

time just prior to the arrival of the side-reflected component. Figures 4 and 5 depict samples of the received signal at frequencies of 75.85 kHz and 107.5 kHz, respectively. Some residual interference effects appeared to be present upon analysis of the data, but their effects were relatively small and did not seriously degrade the overall results.

The source transducer was maintained at the same position during all data collection. Trial movements of the source for purposes of determining positional effects and received signal component identification were accomplished prior to actual data collection. The amplification factor for the received signal was also held constant at 40 dB so that all signal amplitudes, V, refer to the uncorrected, peak-to-peak voltage measured on the oscilloscope. The estimated uncertainty of these measurements was ±5 mv during the first stage of the experiment wherein signal amplitudes commonly exceeded 0.4 volts. During subsequent stages, signal amplitudes were generally less than 0.2 volts and were measured with an accuracy of ±2.5 mv. The estimated uncertainty in the receiver position was plus or minus one millimeter in all directions throughout the experiment. Error symbols on the graphical plots indicate the undertainty in the data. The lines drawn between data points were sketched as a visual aid only.

B. FIRST STAGE RESULTS

The first stage of the experiment was conducted under the following conditions:

1. Upper layer depth before beginning taper .... 4.0 cm
2. Distance from source to beginning of taper ... 23.5 cm
3. Slope of taper 0.0398
4. Length of tapered section .... 100.4 cm
5. Frequency .... 75.85 kHz
6. Pulse duration .... 0.1 msec
7. Pulse repetition rate .... 100 Hz

The received acoustic signal amplitude was measured at depth increments of 0.5 cm along the longitudinal centerline of the tank, beginning at a position directly below the vertex of the upper layer taper (x = 0.0). These measurements were repeated at intervals of 5 cm along the centerline until a horizontal distance of 105 cm from the vertex was reached. Additional measurements were taken at selected positions when better definition of the acoustic field was desired. All of the data collected during this stage of the experiment were obtained within a period of eight hours.

The relative size of the receiver prevented a thorough sampling of signal amplitudes in the tapered section of the upper layer but the data obtained strongly indicate that first mode propagation predominated. The size of the source and its positioning at half-depth in the upper layer are factors that contribute to the suppression of the second and higher numbered modes so that the predominance of the first mode is reasonable.

A preliminary analysis of the data revealed that, at horizontal distances greater than 25 cm from the vertex, the decrease in signal amplitude was approximately exponential with depth. This was confirmed by making comparative plots of V (at Z = 0.0) multiplied by exp[-Z] versus depth (Z). Such behavior corresponds to the theoretical "tailing off" of the normal mode structure in the upper layer.

A marked change in the variation of signal amplitude with depth in the lower layer occurred between horizontal distances of 25 cm and 15 cm from the vertex of the taper. Signal amplitude measurements at distances between 25 cm and 20 cm revealed no discernible pattern for the amplitude variation. Commencing at approximately x = 20 cm, however, the depth corresponding to maximum signal amplitude increased at a relatively uniform rate as the horizontal distance to the vertex of the taper decreased. The relative shapes of the plots of signal amplitude vs. depth in this region are also indicative of a beam-like directional transmission of acoustical energy originating at a horizontal distance of approximately 18 to 20 cm from the vertex of the taper. (See Fig. 6.) The calculated cutoff depth for the first mode at a frequency of 75.85 kHz is 0.82 cm. This thickness in the upper layer corresponds to a horizontal distance of 20.6 cm from the vertex of the taper. This distance relates remarkably well to the estimated origin of energy transmission based upon the experimental data.

Graphs 1 through 4 are plots which were designed to facilitate an estimation of the apparent angle of energy transmission in the vertical plane. These plots of experimental data were constructed using the following scaling criteria:

1. Signal amplitudes (V) were assumed to have suffered cylindrical spreading losses over the distance (r) from the estimated origin of the apparent beam to the point of measurement. (Refer to Fig. 1.) The horizontal coordinate of a datum therefore represents the signal amplitude extrapolated back to a distance of one centimeter from the apparent origin.

2. The depth (Z) at which the amplitude measurement was made was divided by the horizontal distance (x') from the assumed origin of the beam. The vertical coordinate of a datum therefore represents the tangent of a depression angle measured from the horizontal plane.

3. The origin of the apparent beam was assumed to be at a horizontal distance of 20 cm from the vertex of the taper. Transmission of acoustical energy into the lower layer may have occurred over a distance of approximately 4.0 cm centered about this origin.

The assumption of cylindrical spreading was considered consistent with the spreading exhibited by the main beam of a line-like source at relatively short ranges.

A sequential examination of Graphs 1 through 3 indicates that the beam-like transmission pattern was not well defined until a distance of approximately 10 cm from the estimated

origin was reached. At longer distances the pattern was better defined and the data plots were relatively similar when the possible variance due to measurement errors was considered. The finer structure of the plots is believed to be due, in part, to residual multi-path interference effects discussed earlier in this report.

Because of the geometric factors involved in the scaling of the data, uncertainty in the estimated position of the beam origin can result in considerable error when determining the values of x' and r. The relative magnitude of these errors increases as the horizontal distance from the estimated origin decreases. Data corresponding to values of x' less than 10 cm were therefore excluded when estimating apparent angles of transmission and beamwidths. These parameters were estimated by analyzing an overlay of the data corresponding to values of x' greater than or equal to 10 cm, as depicted on Graph 4. A datum corresponding to the average maximum amplitude of the combined data was estimated by averaging numerically the individual maximum amplitude ($Vr^{1/2}$) data. The vertical coordinate of the estimated datum was then used to provide the first estimate of the beam depression angle. The 3 dB down points were subsequently estimated in a similar manner using the horizontal coordinate of the maximum amplitude datum as a reference. The depression angles corresponding to these points thus provided an estimate of the apparent beamwidth.

A second estimate of the beam depression angle was obtained by bisecting the angle between the 3 dB down points. Table I provides a list of the estimated depression angles and beamwidths for all stages of the experiment.

The foregoing estimates are, of course, subject to some error. Analysis of the geometry suggests that the apparent angle of transmission could be in error by about ±2 degrees if the estimated origin of the transmission had an uncertainty of ±2.0 cm. The estimated angular concentration of transmitted energy (beamwidth) can reasonably be expected to reflect a similar percentage of error.

A period of five days elapsed between the conclusion of the first stage of the experiment and the commencement of further experimentation. During this period the temperature of the building in which the test tank was located was considerably lower than normal. A thin film of unidentified substance formed along the oil-brine interface during this period, possibly as a result of the temperature reduction. A repetition of the first-stage amplitude measurements at selected positions revealed that the transmission patterns were relatively unchanged but signal amplitudes in the apparent beam were reduced by approximately 60%. Signal amplitudes in the upper layer at short distances from the source, however, were virtually unchanged. Graphs 5 and 6 depict typical data obtained during a repetition of the first stage. The data obtained at corresponding positions during

the first stage were reduced by 60% and superimposed on the graphs for comparative purposes using plus signs (+). Visual examination suggests that while amplitudes have been reduced, the basic features of the transmission remain essentially unchanged. The resultant estimates of depression angle and beamwidth listed in Table I further support this contention.

C. EFFECTS OF FREQUENCY AND SLOPE VARIATIONS

The second stage of the experiment was carried out in a manner identical to the first stage with the following changes in conditions:

1. Frequency .... 107.5 kHz
2. Pulse duration .... 0.15 msec

In accordance with the definition of the modal cutoff depth given previously, the following cutoff depths and distances were computed:

$h_1 = 0.578$ cm $\qquad x_1 = 14.52$ cm

$h_2 = 1.734$ cm $\qquad x_2 = 43.55$ cm

$h_3 = 2.89$ cm $\qquad x_3 = 72.6$ cm

Data were then collected at appropriate locations to determine whether beam-like transmissions originated at these positions. This resulted in the identification of transmissions related to the first and third modes. The

absence of the second mode was expected but the relatively large magnitude of the third mode transmission was somewhat surprising.

Scaled plots of the experimental data were constructed in the same manner as those for the first stage. Graphs 7 through 10 relate the to the first mode transmission. The origin of the apparent beam was estimated to be at a horizontal distance of 12 cm (±2 cm) from the vertex of the taper which is fairly consistent with the theoretical distance. Refer to Table I for estimates of beam parameters. Graphs 11 through 13 relate to the third mode transmission. The estimated origin of the beam was at a horizontal distance of 70 cm (±2 cm) from the vertex which is, again, consistent with the predicted position. Corresponding beam-width and depression angle estimates are listed in Table I.

The final stage of the experiment was conducted under the following conditions:

1. Upper layer depth prior to taper .... 4.0 cm
2. Distance from source to beginning of taper ..... 47.4 cm
3. Slope of taper 0.052
4. Length of tapered section .... 76.3 cm
5. Frequency .... 75.85 kHz
6. Pulse duration .... 0.1 msec
7. Pulse repetition rate .... 100 Hz

The procedures utilized were identical to those in the previous stages.

The cutoff depth for the first mode was the same as that computed for the first stage since the frequency was the same. In this case, however, the distance from the vertex of the taper is reduced to 15.6 cm by virtue of the change in the slope. Based upon the data obtained, the estimated origin of the apparent beam was approximately 15 cm (±2 cm) from the vertex. Graphs 14 through 16 depict the corresponding scaled data plots for the new slope conditions which were analyzed as before. The resultant estimates of beam width and depression angle are listed in Table I.

IV. CONCLUSIONS

The data obtained during this preliminary investigation were sufficient to support the following conclusions:

1. The transmission of acoustical energy from a tapered fluid layer overlying an essentially semi-infinite fluid layer with higher sound speed is concentrated within relatively well defined regions along the fluid-fluid interface.

2. The regions of concentrated transmission correspond to the modal cutoff depths which are frequency dependent. The positions of these regions may therefore be predicted with reasonable accuracy when the properties of the fluids and the slope of the taper are known.

3. The transmission of acoustical energy into the lower fluid layer within these regions exhibits directional properties which indicate that a beam-forming process may occur over the length of the transmission region.

4. Additional data for larger ranges of frequency and slope would be required to draw any firm conclusions regarding their influence on the beamwidth/depression angle of the beam sent into the bottom.

APPENDIX A

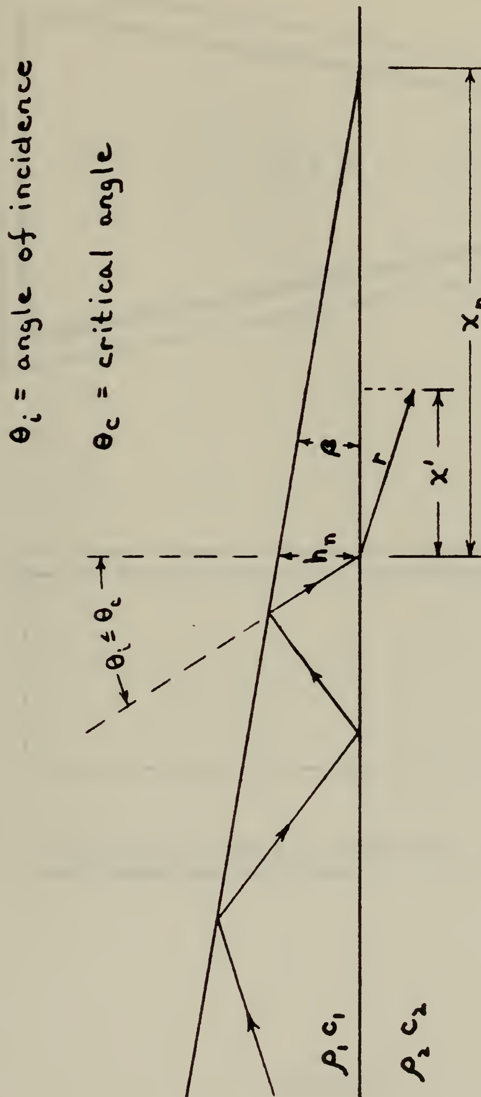
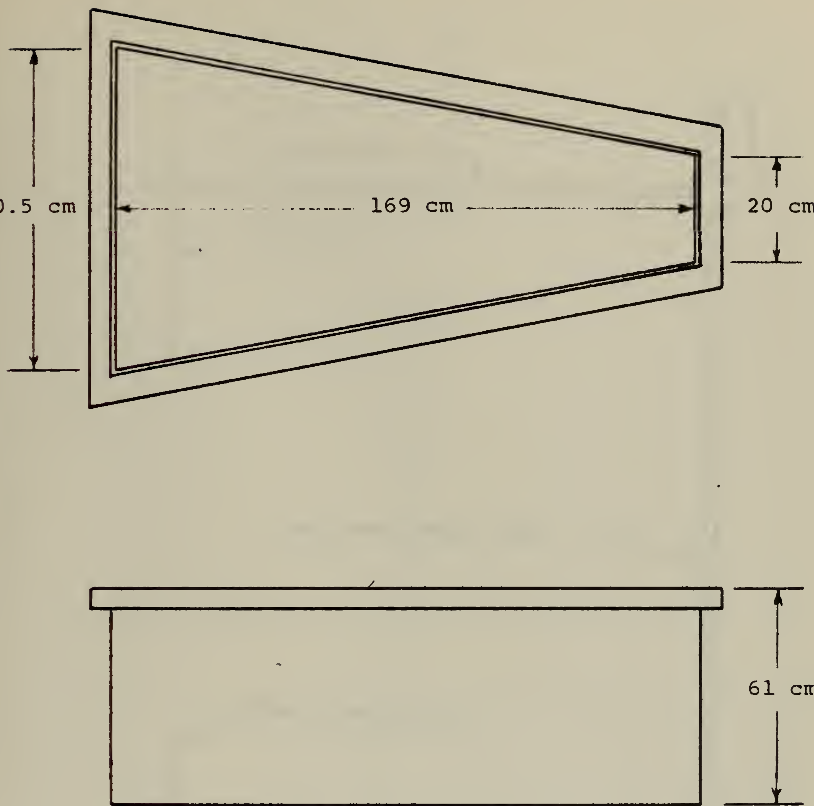


Figure 1.



Not drawn to scale - supporting struts and tank base are not shown.

Figure 2a.

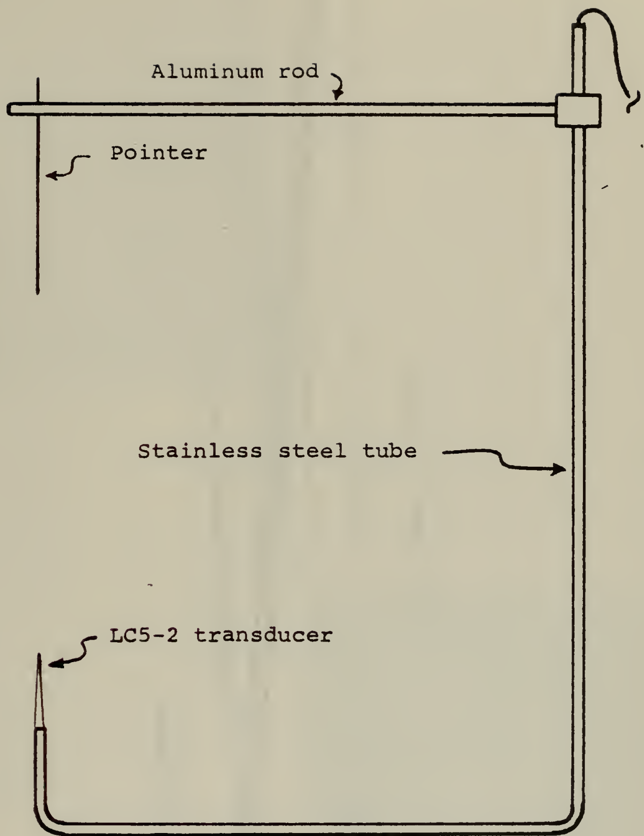

Aluminum rod
Pointer
Stainless steel tube
LC5-2 transducer

Figure 2b.

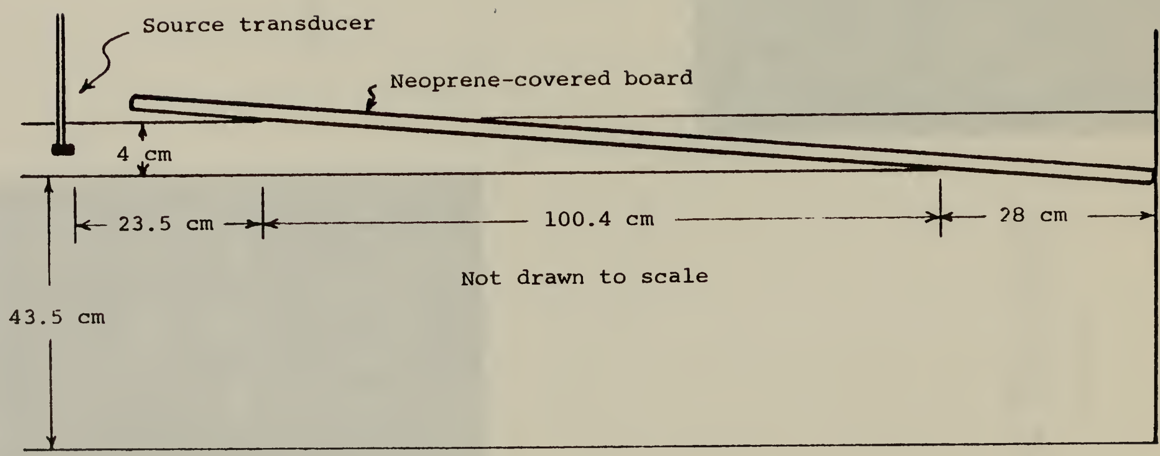

Source transducer
Neoprene-covered board
4 cm
23.5 cm
100.4 cm
28 cm
Not drawn to scale
43.5 cm

Figure 3.

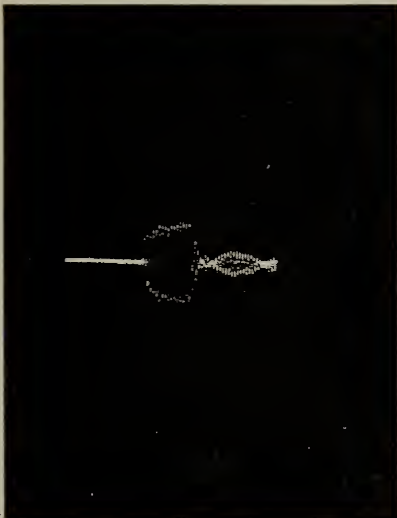
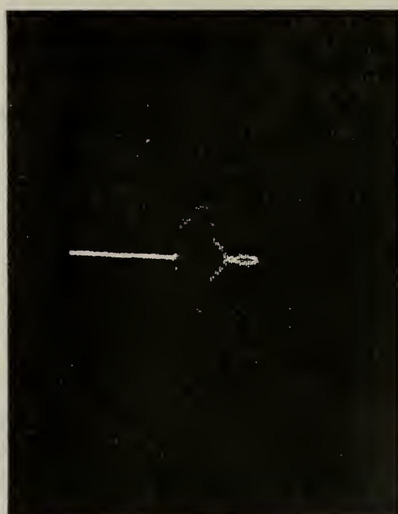


Figure 4.

Typical signal received at F=75.85 kHz.

Figure 5.

Typical signal received at F=107.5 kHz.



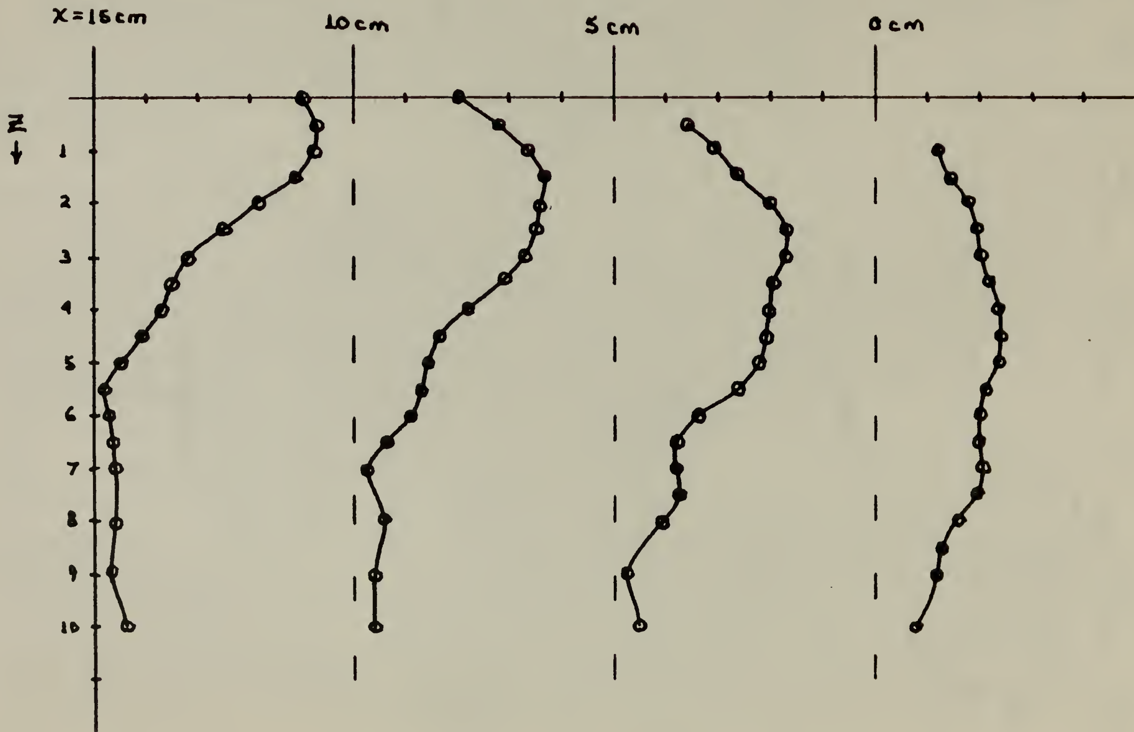
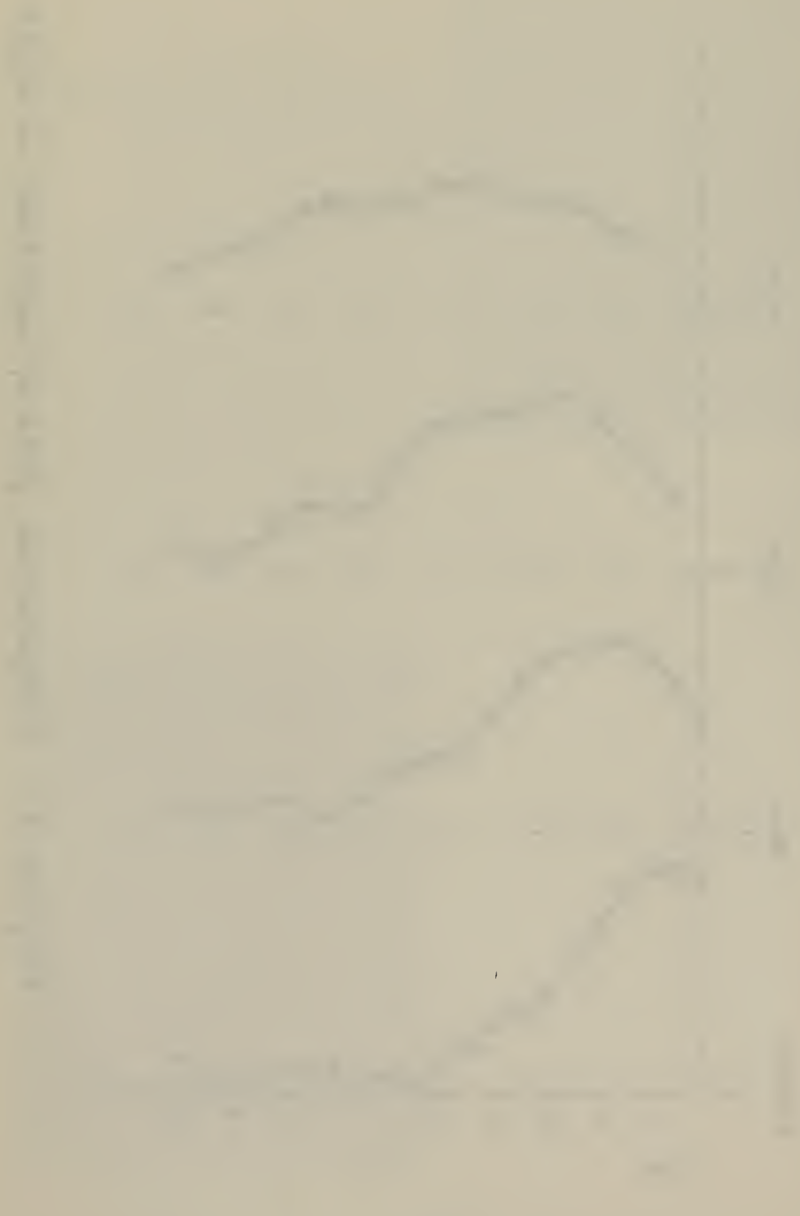
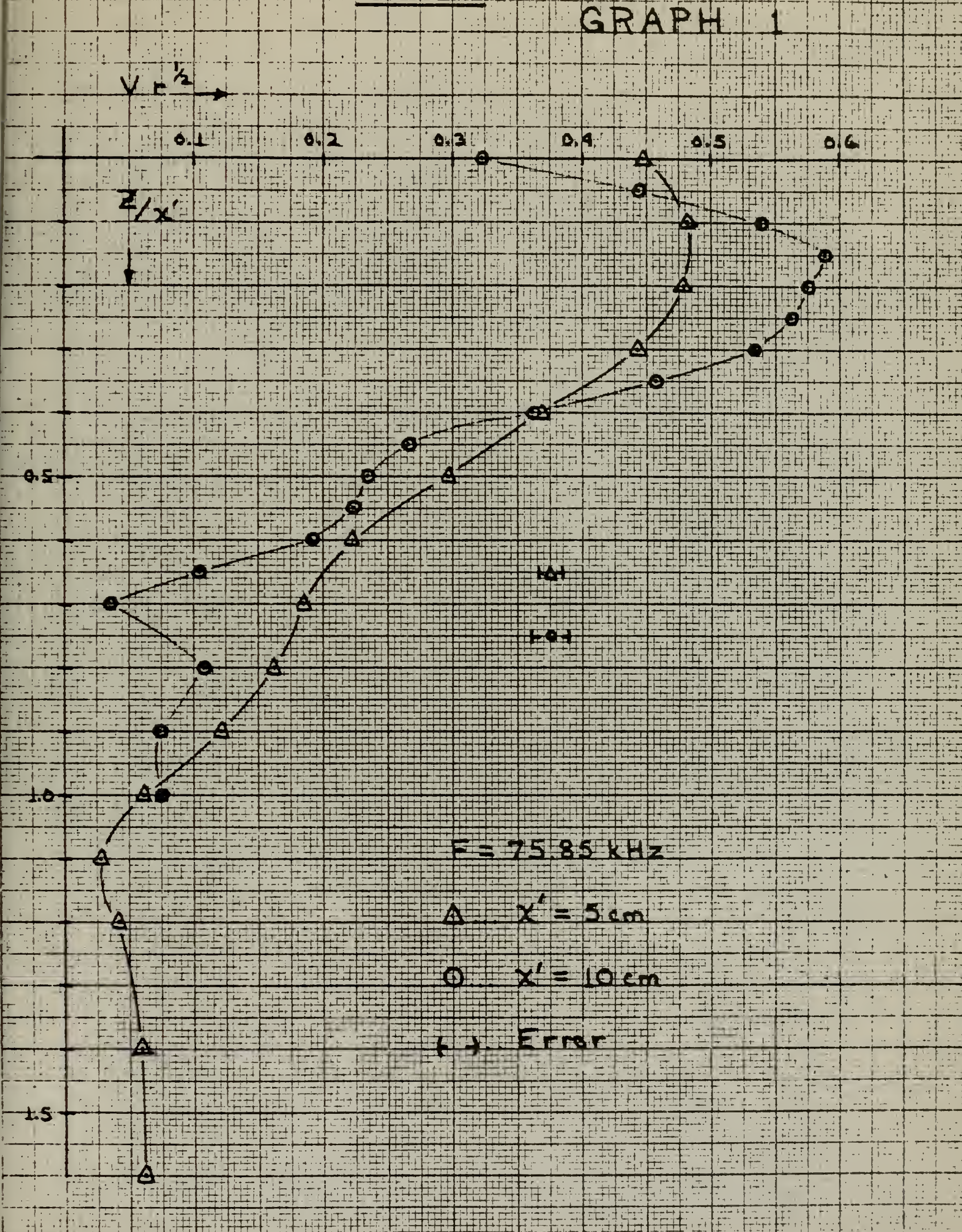
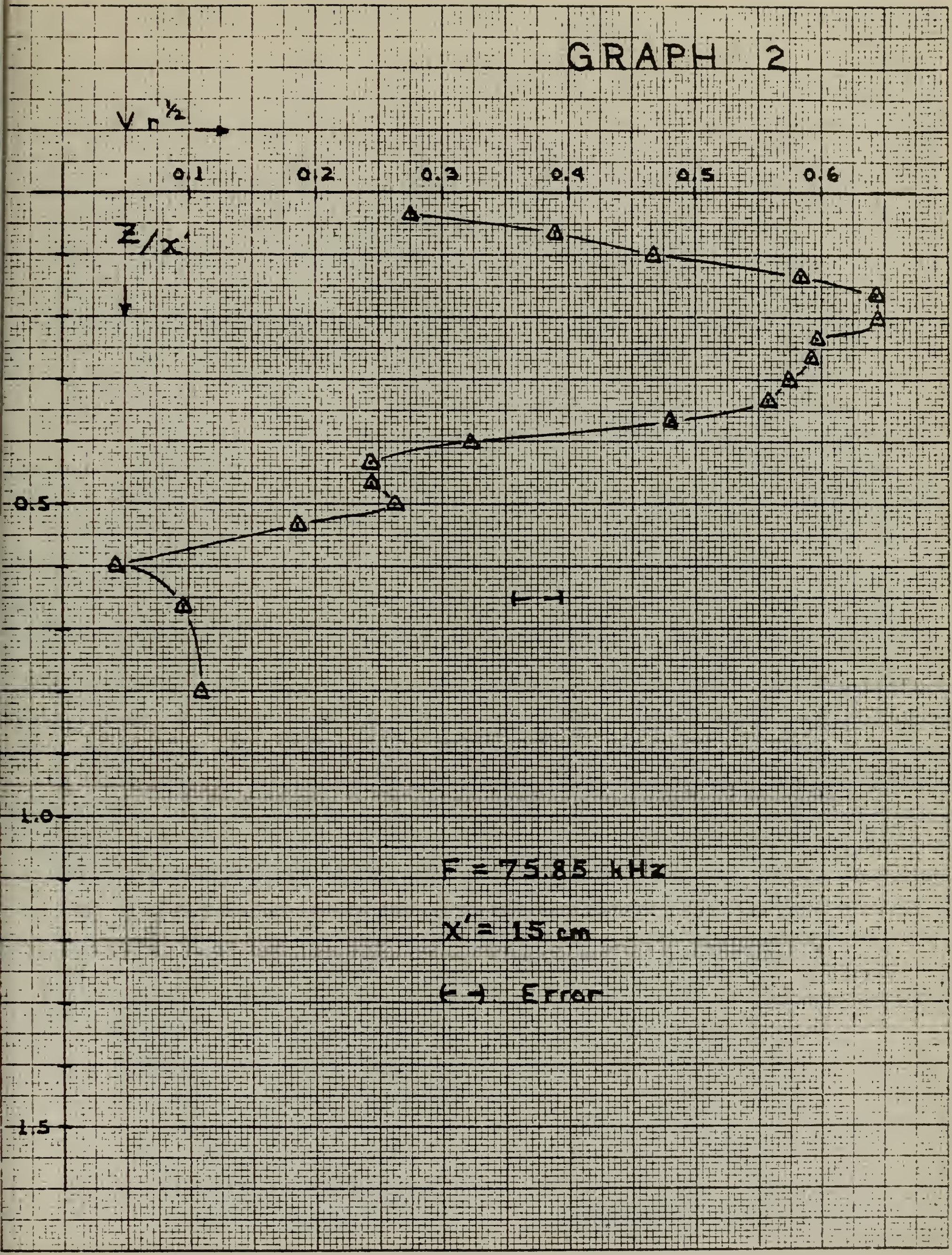


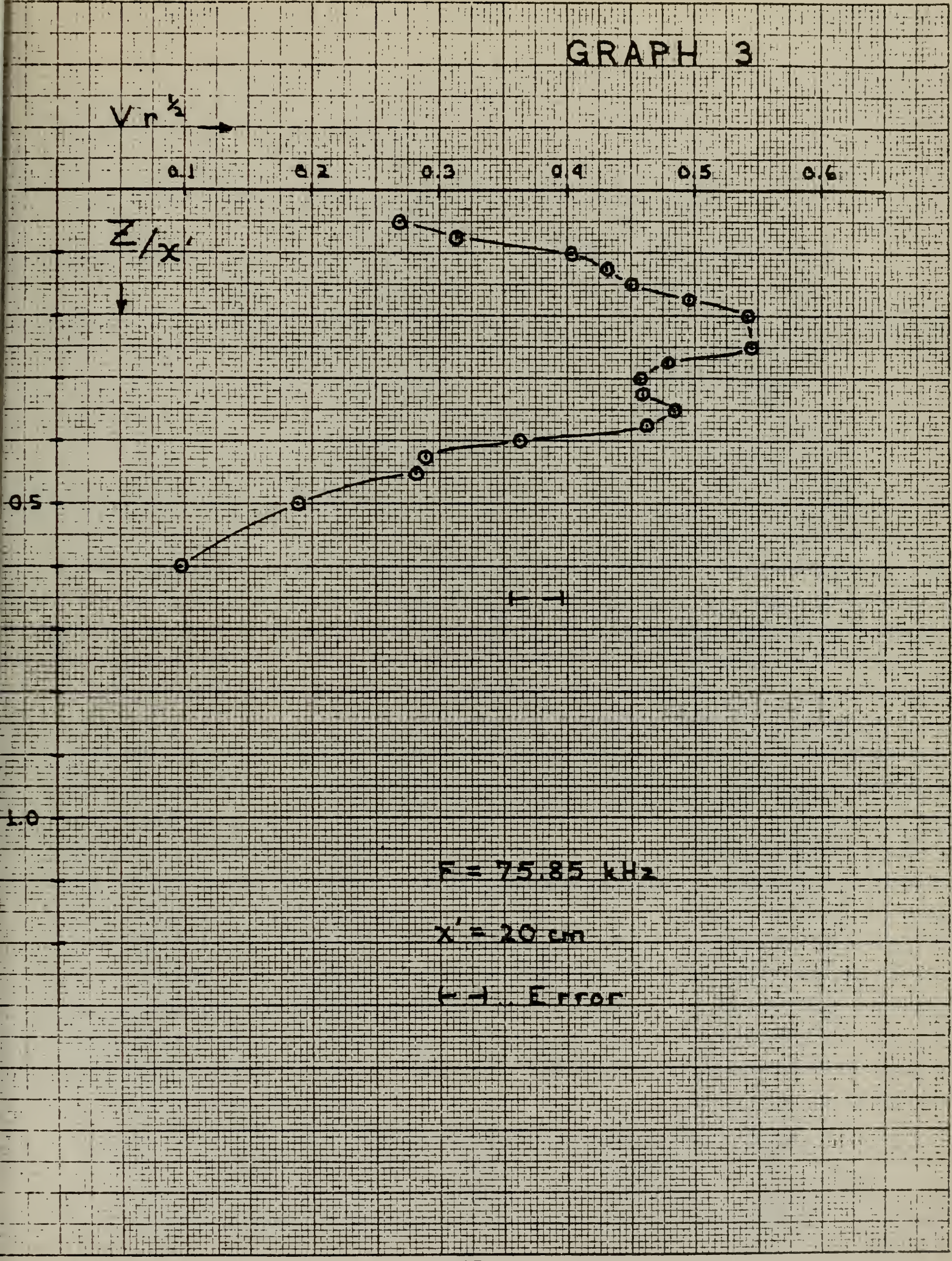
Figure 6 : Comparative plots of amplitude v.s. depth

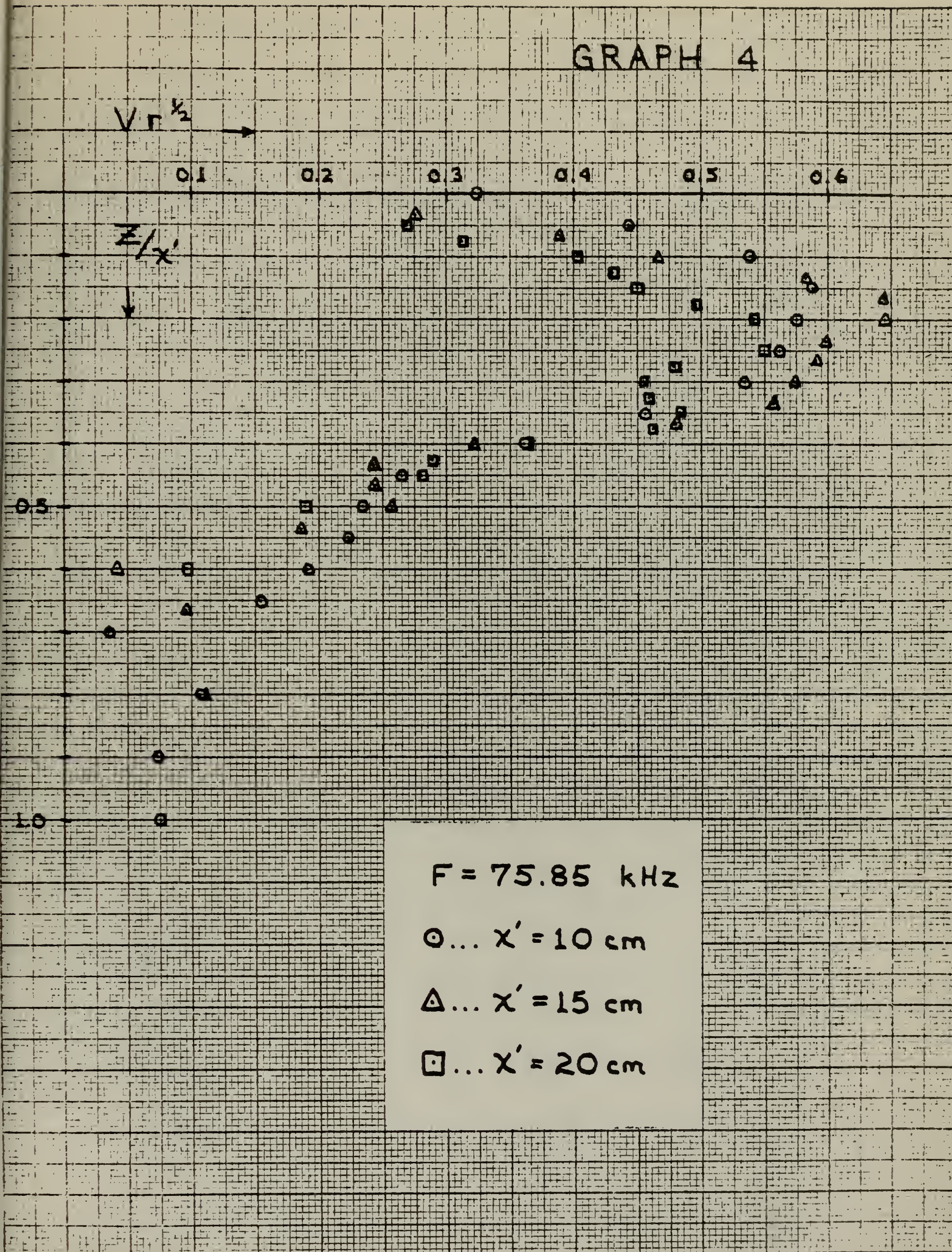


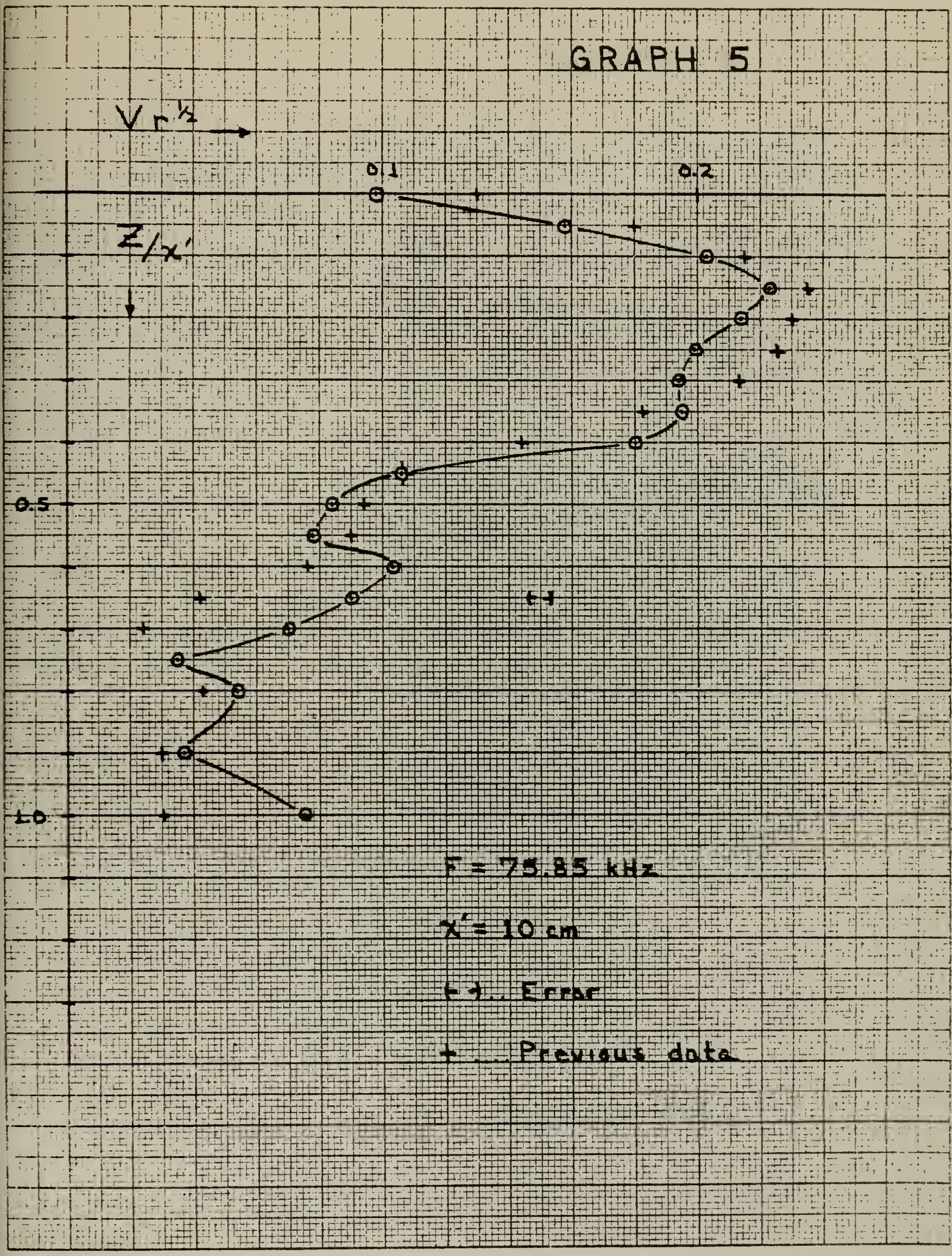
APPENDIX B


GRAPH 1
$V_r^{1/2}$
0.1
0.2
0.3
0.4
0.5
0.6
Z/X'
0.5
1.0
1.5
F = 75.85 kHz
△ ... X' = 5 cm
○ ... X' = 10 cm
( ) ... Error

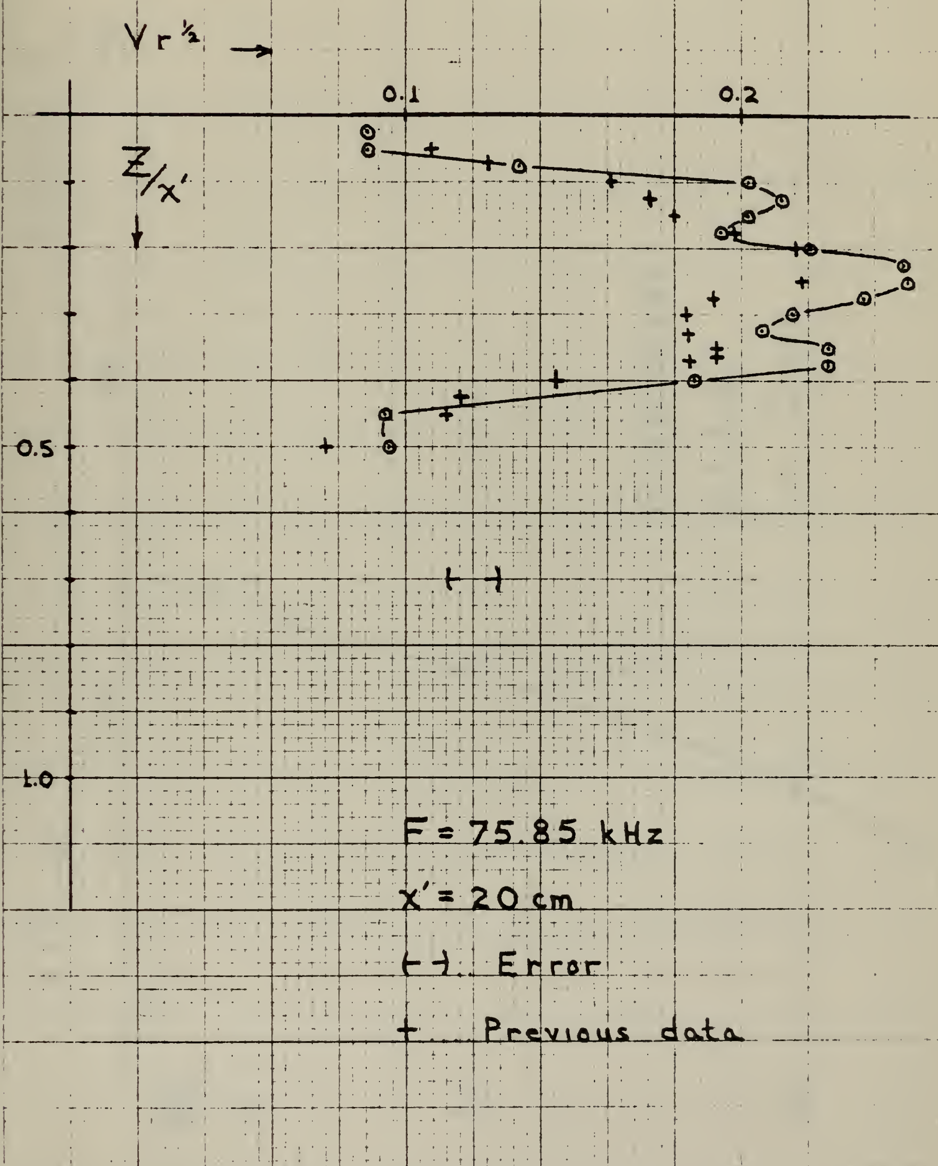

GRAPH 2
$V_n^{1/2}$
0.1
0.2
0.3
0.4
0.5
0.6
Z/x'
0.5
1.0
1.5
F = 75.85 kHz
X' = 15 cm
(⊢⊣) Error

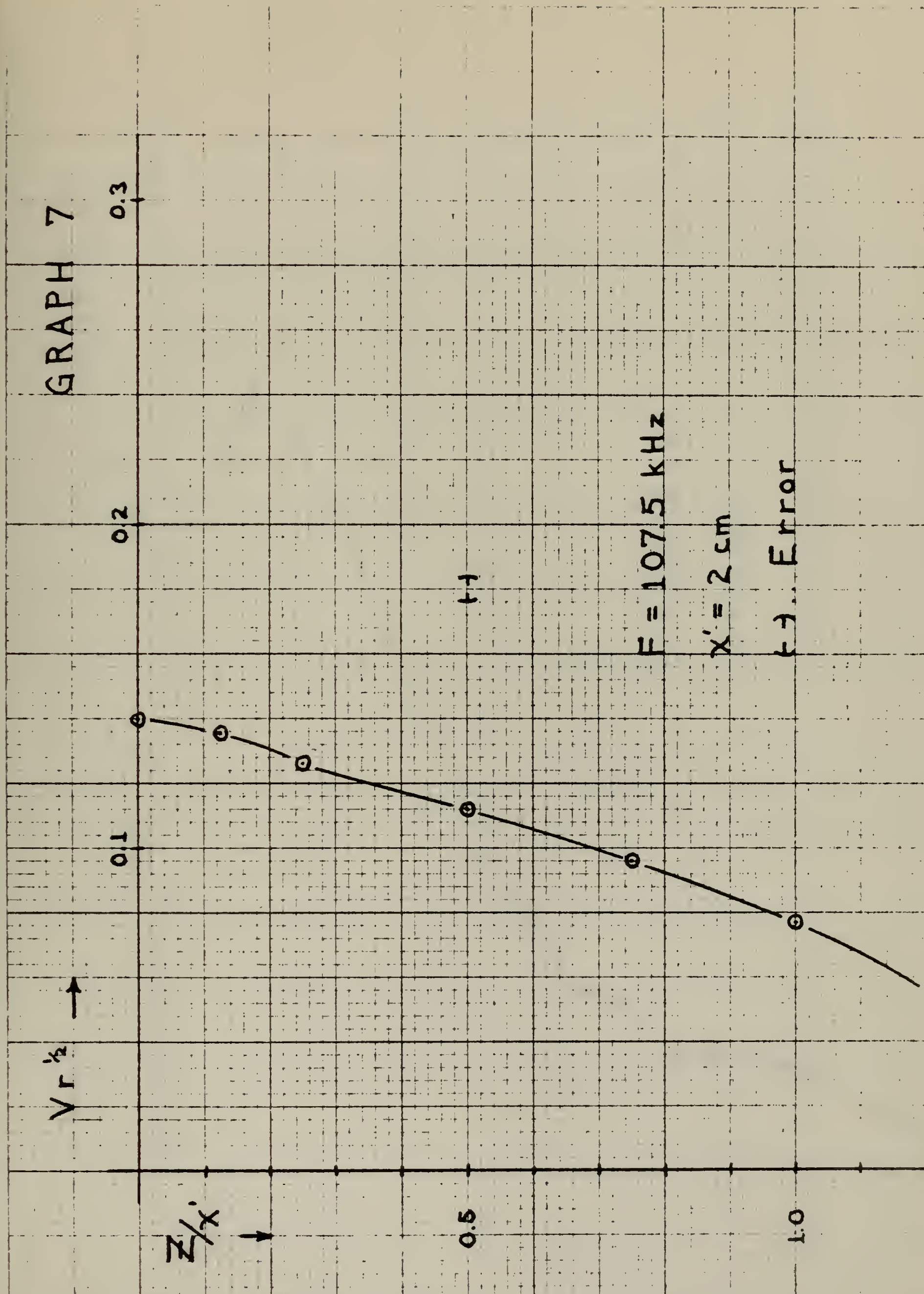

GRAPH 3
$V r^{1/2}$
0.1
0.2
0.3
0.4
0.5
0.6
Z/x'
0.5
1.0
F = 75.85 kHz
x' = 20 cm
⊢⊣ Error

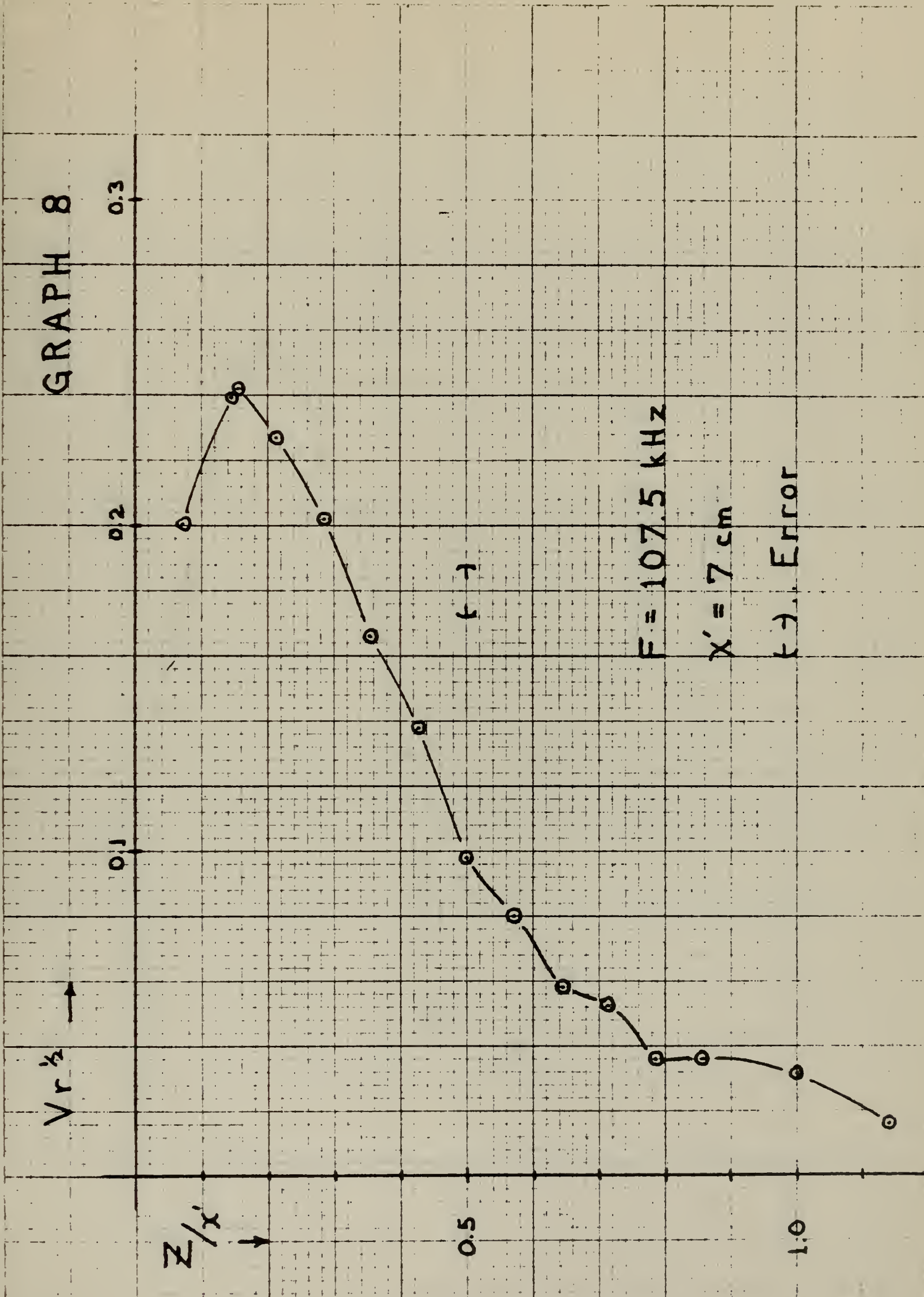

GRAPH 4
$Vr^{1/2}$
0.1
0.2
0.3
0.4
0.5
0.6
Z/x'
0.5
1.0
F = 75.85 kHz
⊙ ... x' = 10 cm
Δ ... x' = 15 cm
⊡ ... x' = 20 cm

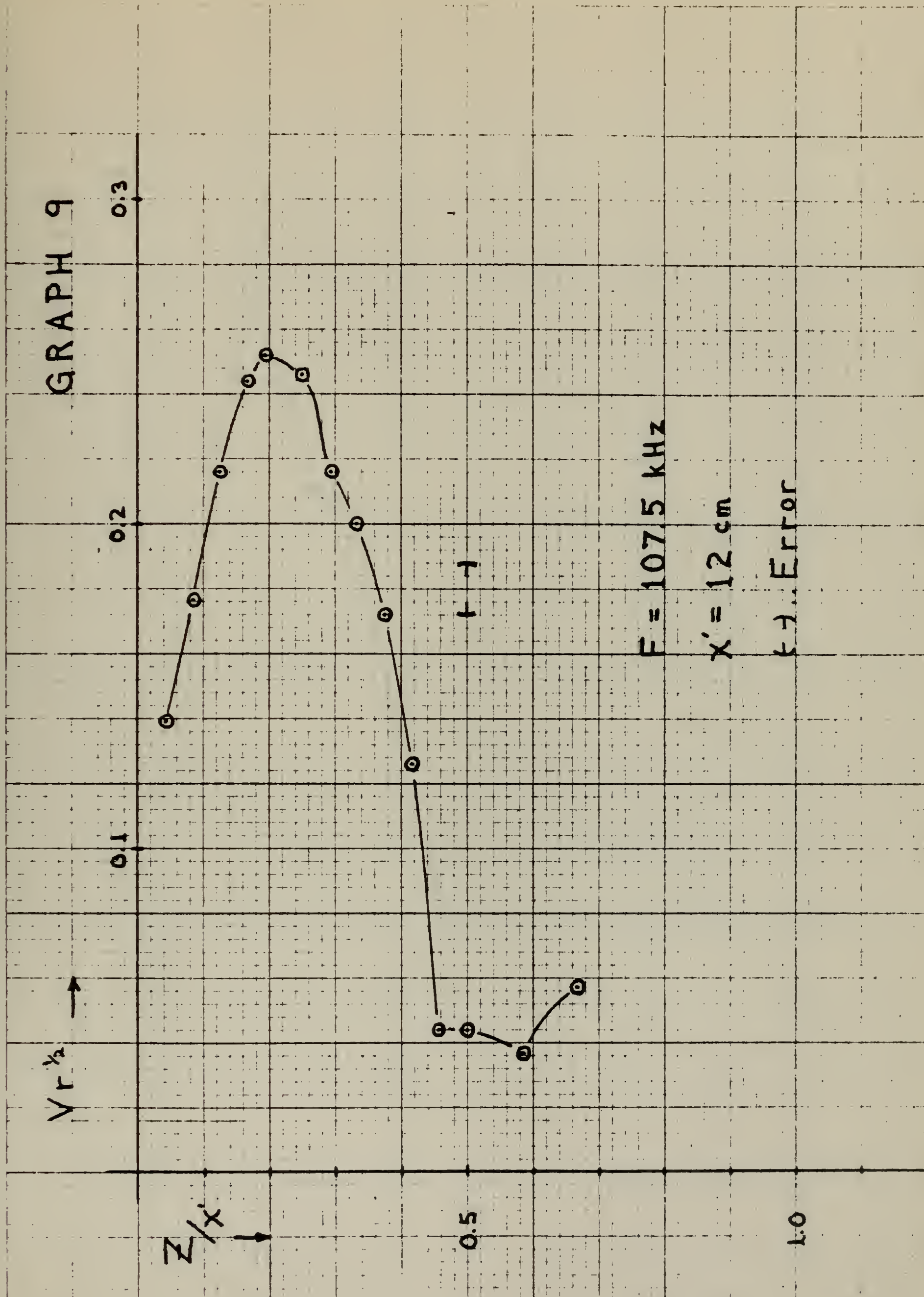

GRAPH 5
Vr^½
0.1
0.2
Z/x'
0.5
1.0
F = 75.85 kHz
x' = 10 cm
⊢⊣ .. Error
+ .... Previous data

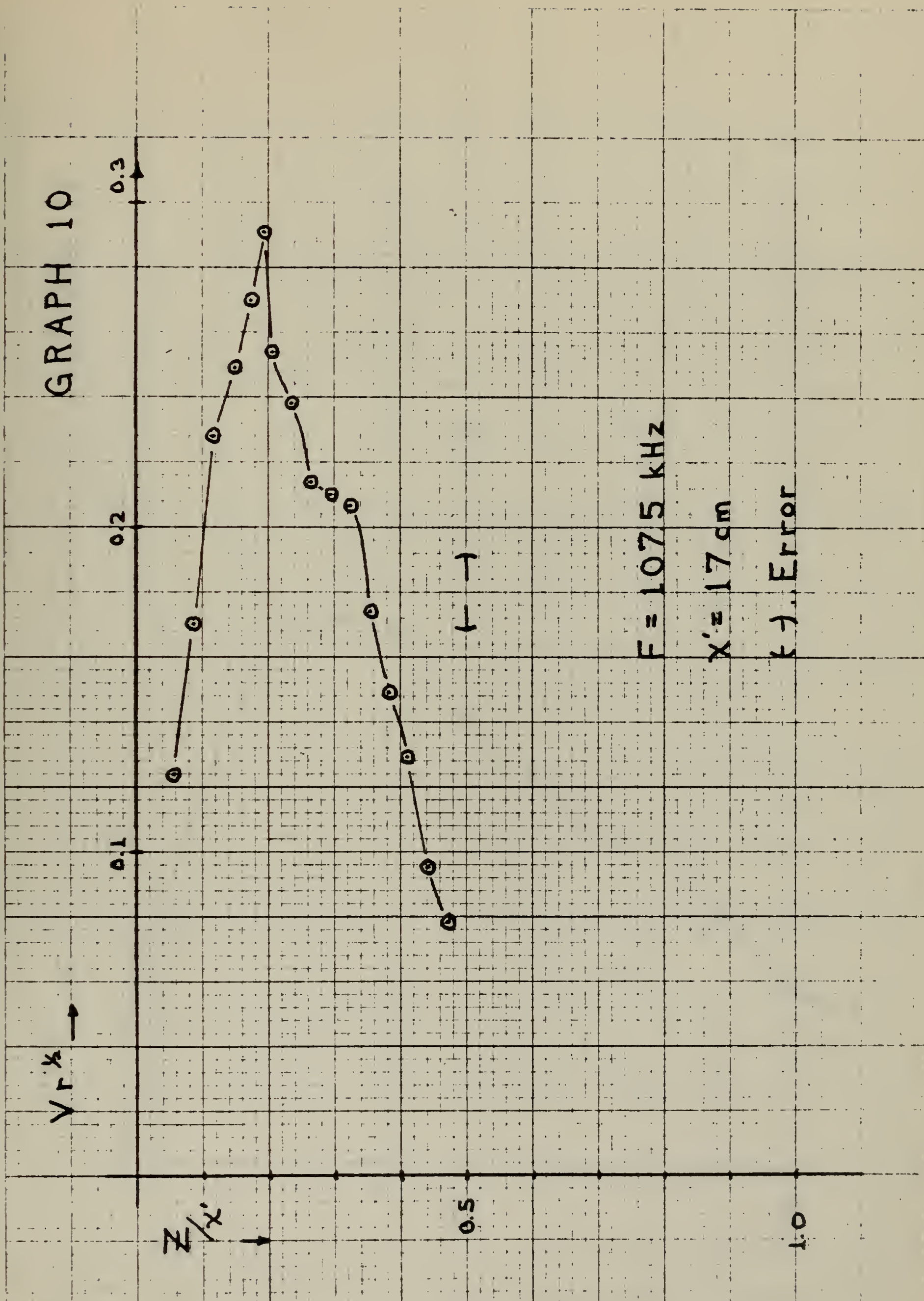
GRAPH 6



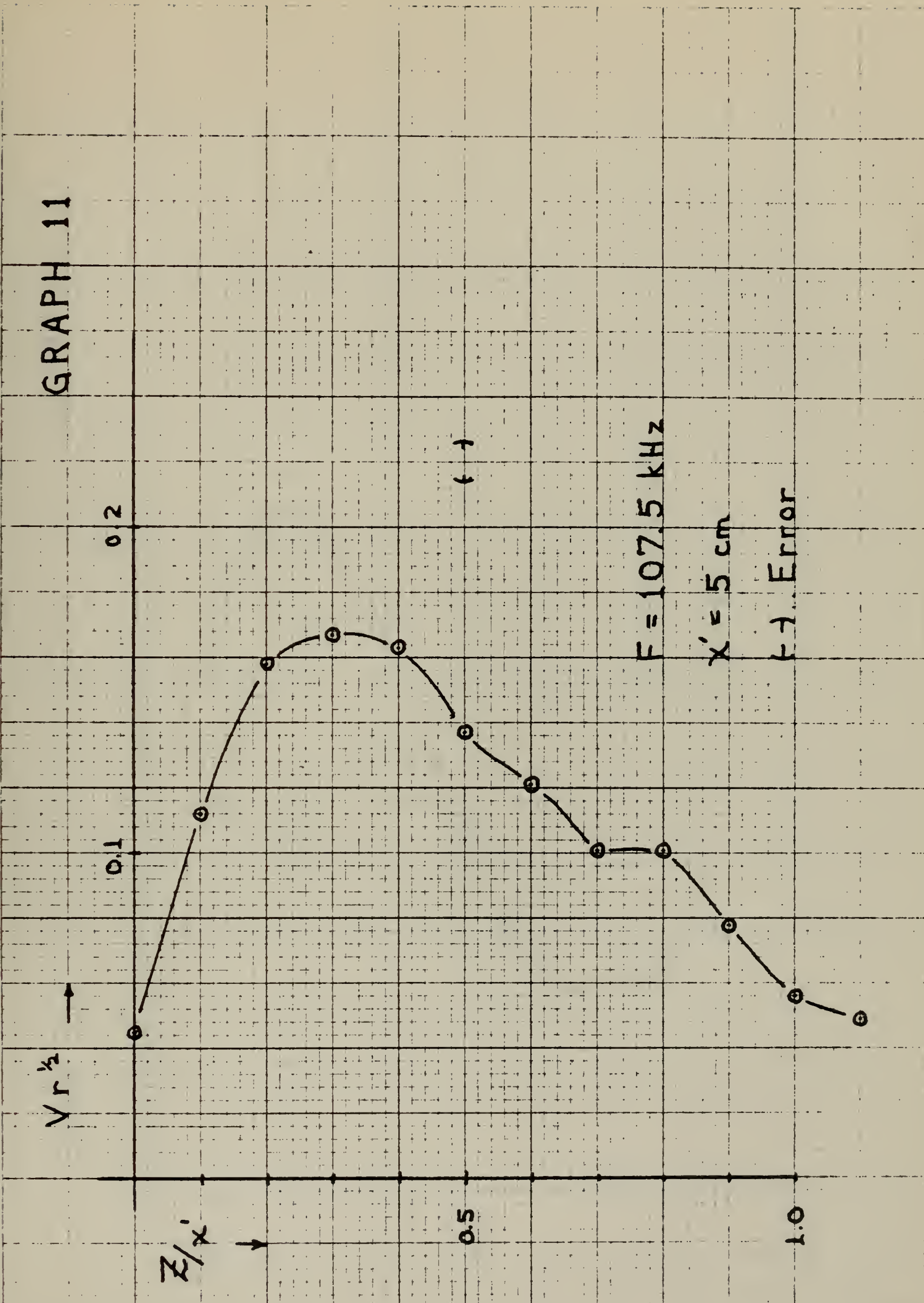

GRAPH 7
F = 107.5 kHz
X' = 2 cm
(-) .. Error
Vr ½ →
Z/X' →
0.1
0.2
0.3
0.5
1.0


GRAPH 8
F = 107.5 kHz
X' = 7 cm
⊢⊣ Error
Vr½ →
Z/X' →
0.1
0.2
0.3
0.5
1.0

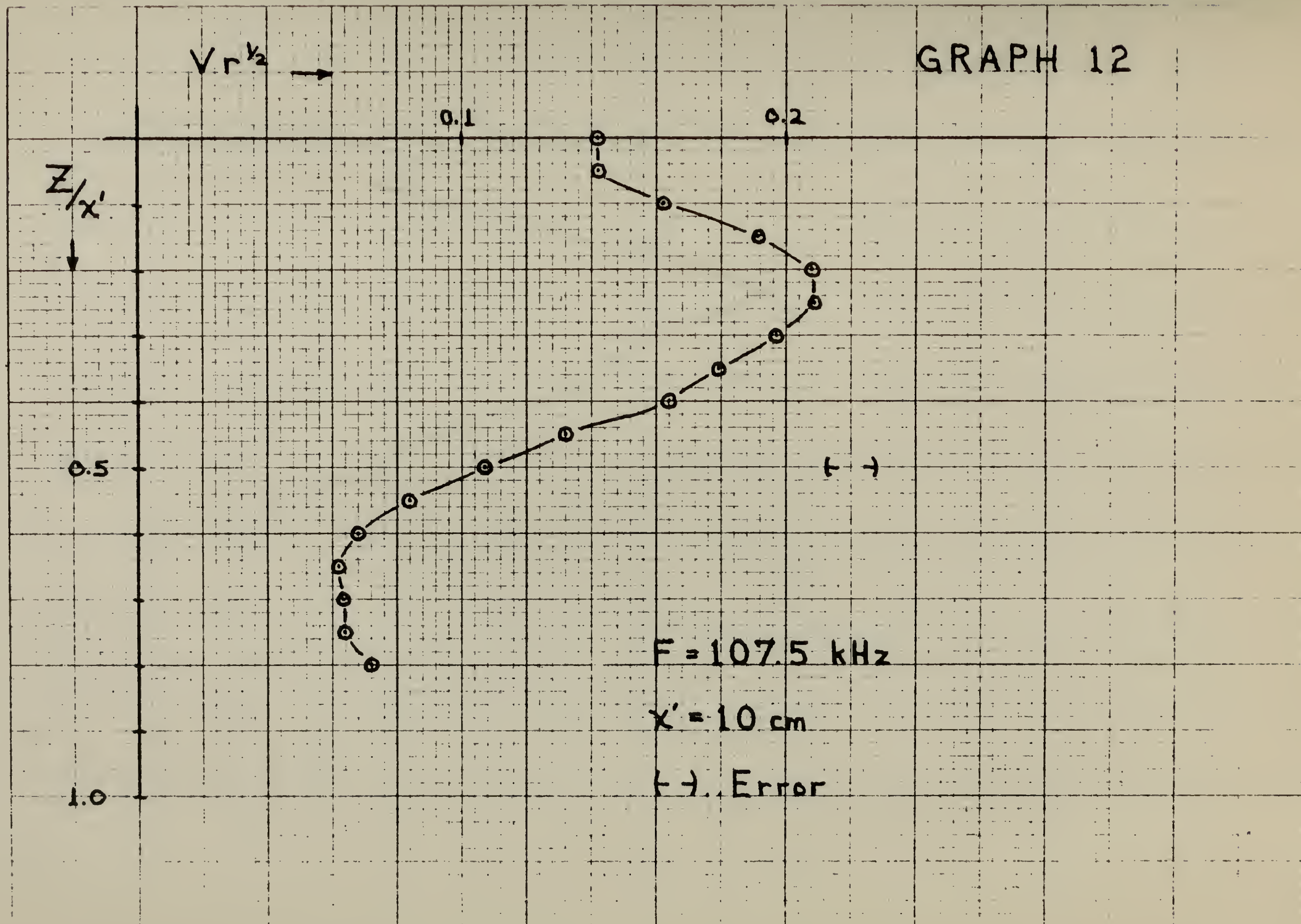

GRAPH 9
$V_r^{1/2}$ →
Z/x' →
0.1
0.2
0.3
0.5
1.0
F = 107.5 kHz
x' = 12 cm
⊢⊣ Error

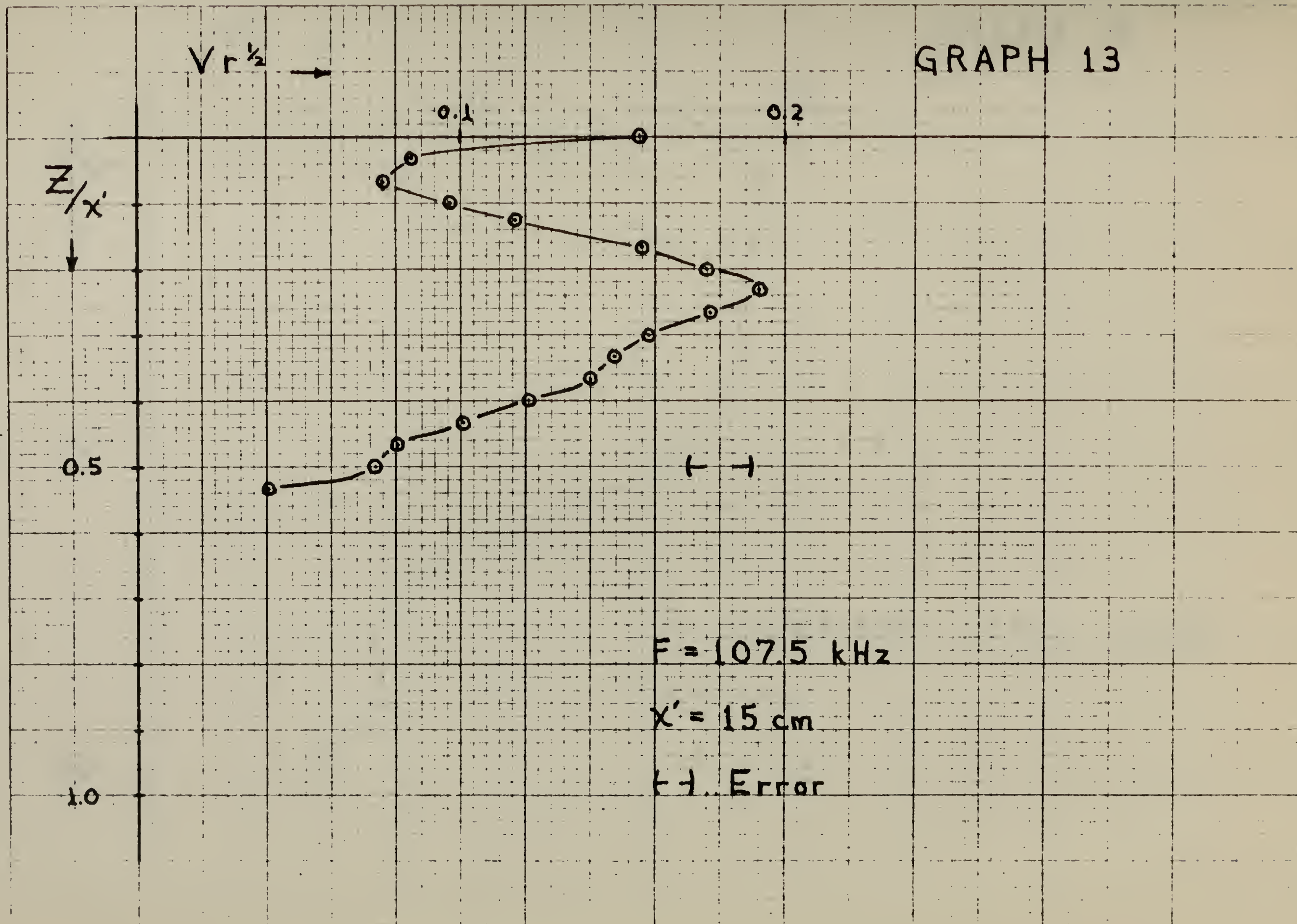


GRAPH 10
F = 1075 kHz
X' = 17 cm
Error
$V_r x$
Z/X'
0.1
0.2
0.3
0.5
1.0

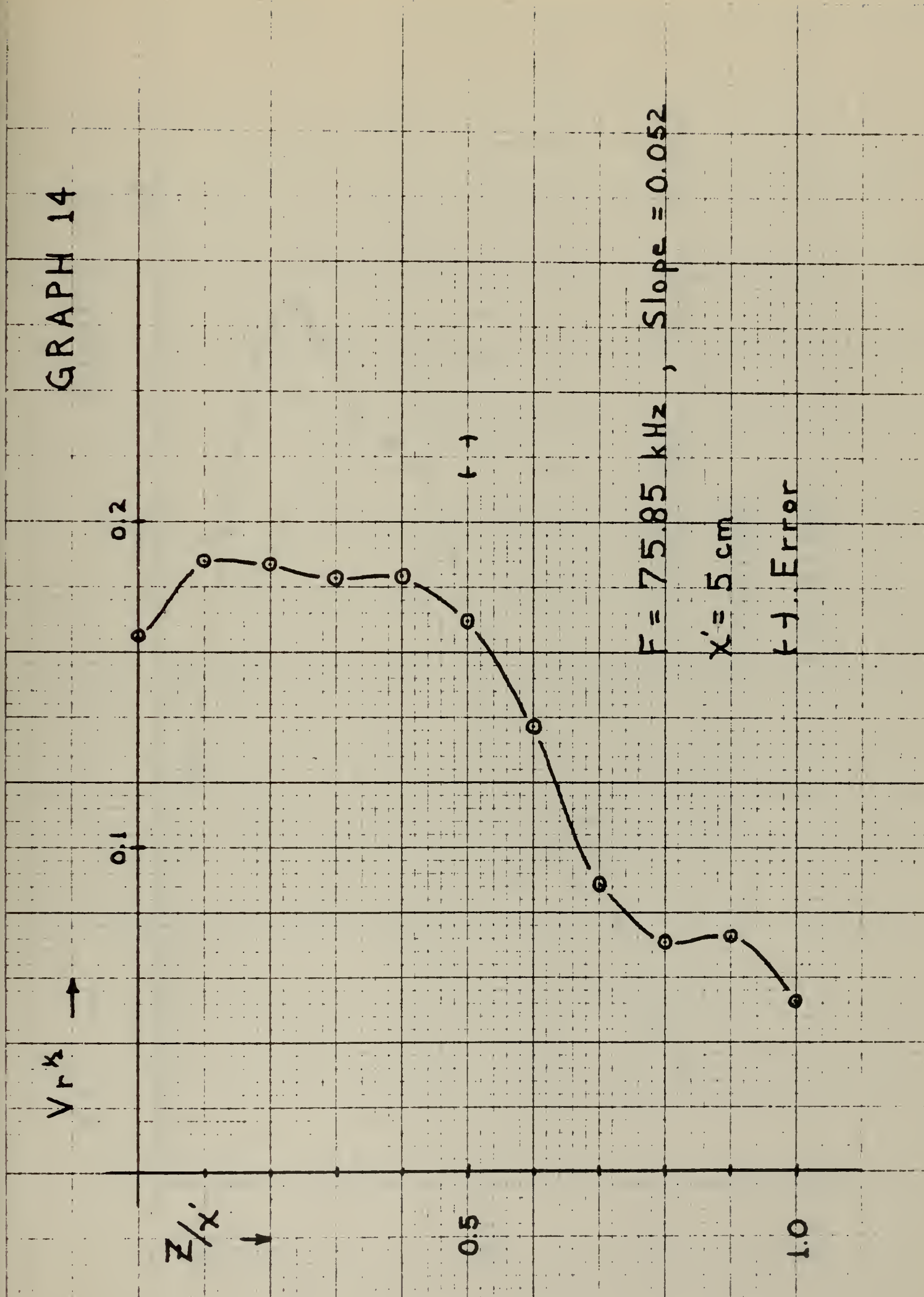


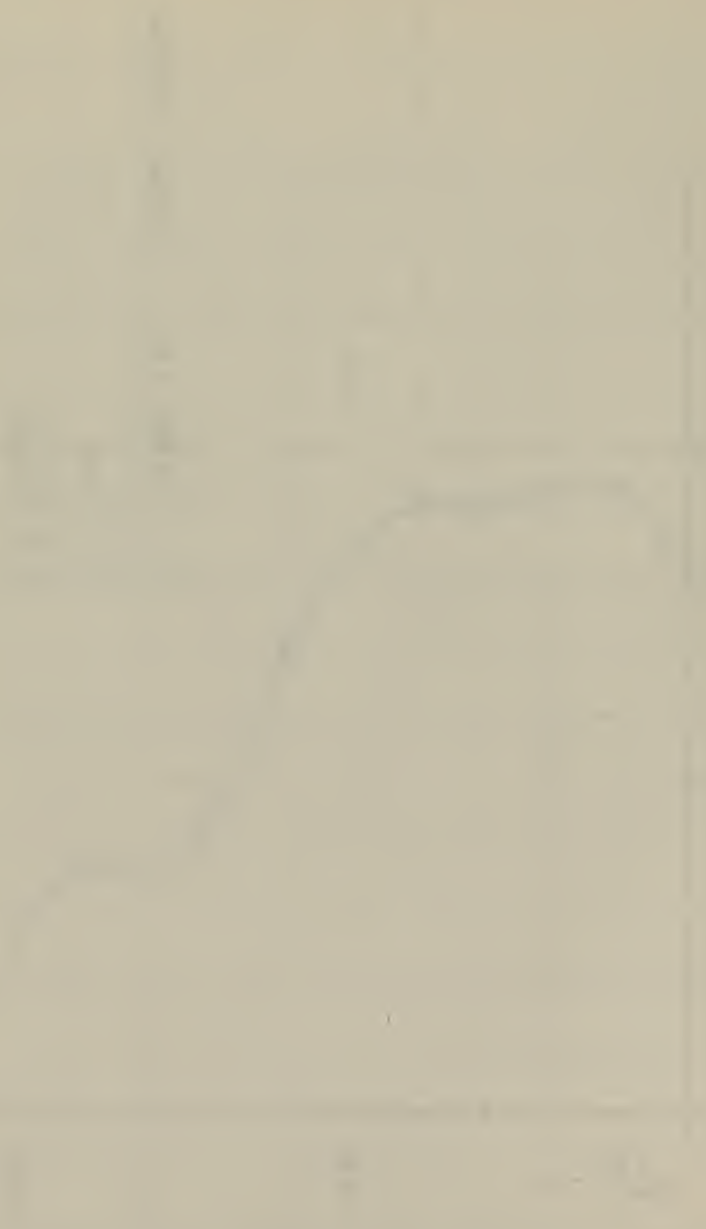
GRAPH 11
$Vr^{1/2}$
0.1
0.2
Z/x'
0.5
1.0
F = 107.5 kHz
x' = 5 cm
(-) Error

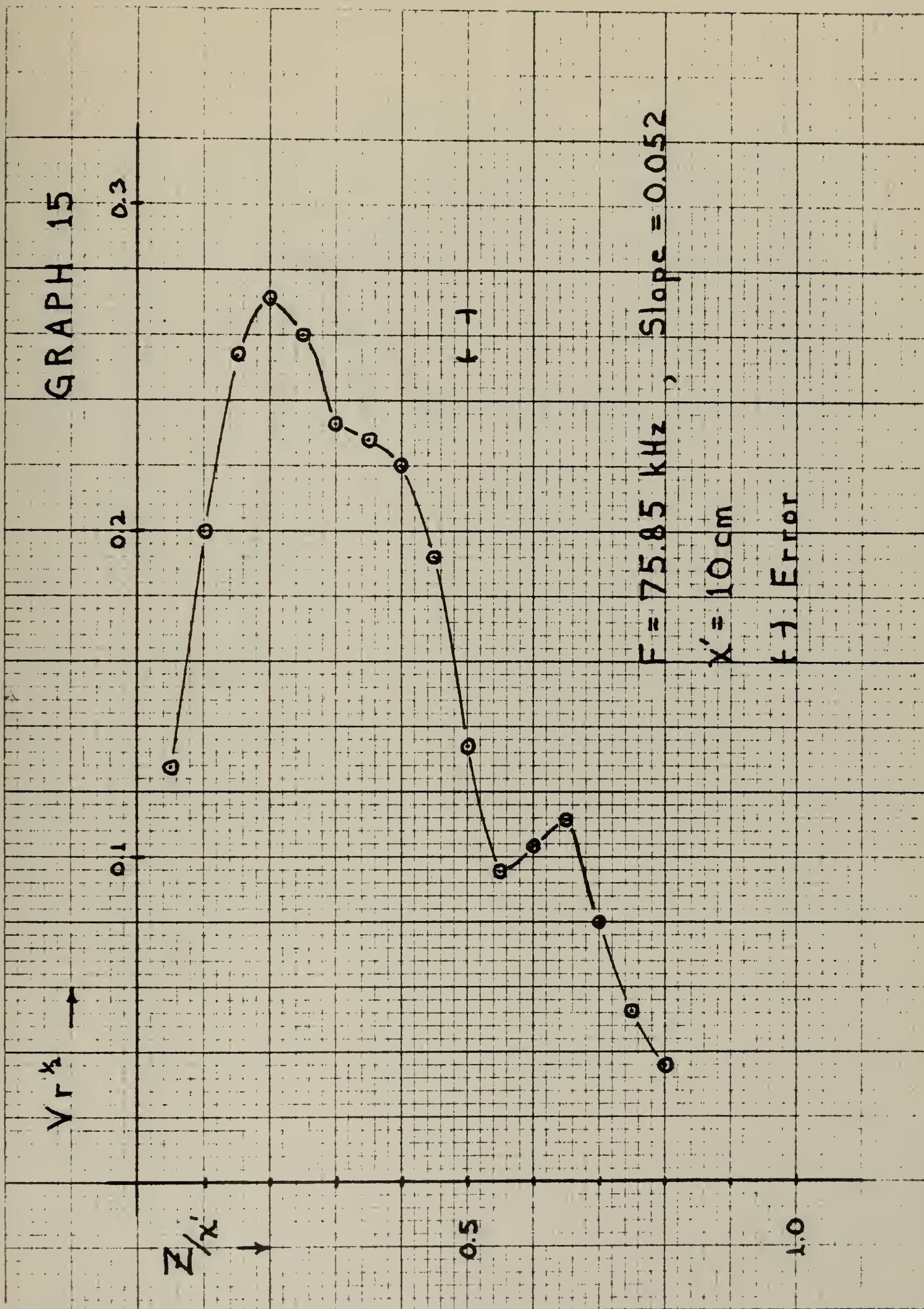

GRAPH 12
Vr½ →
Z/x'
0.1
0.2
0.5
1.0
F = 107.5 kHz
x' = 10 cm
( ). Error



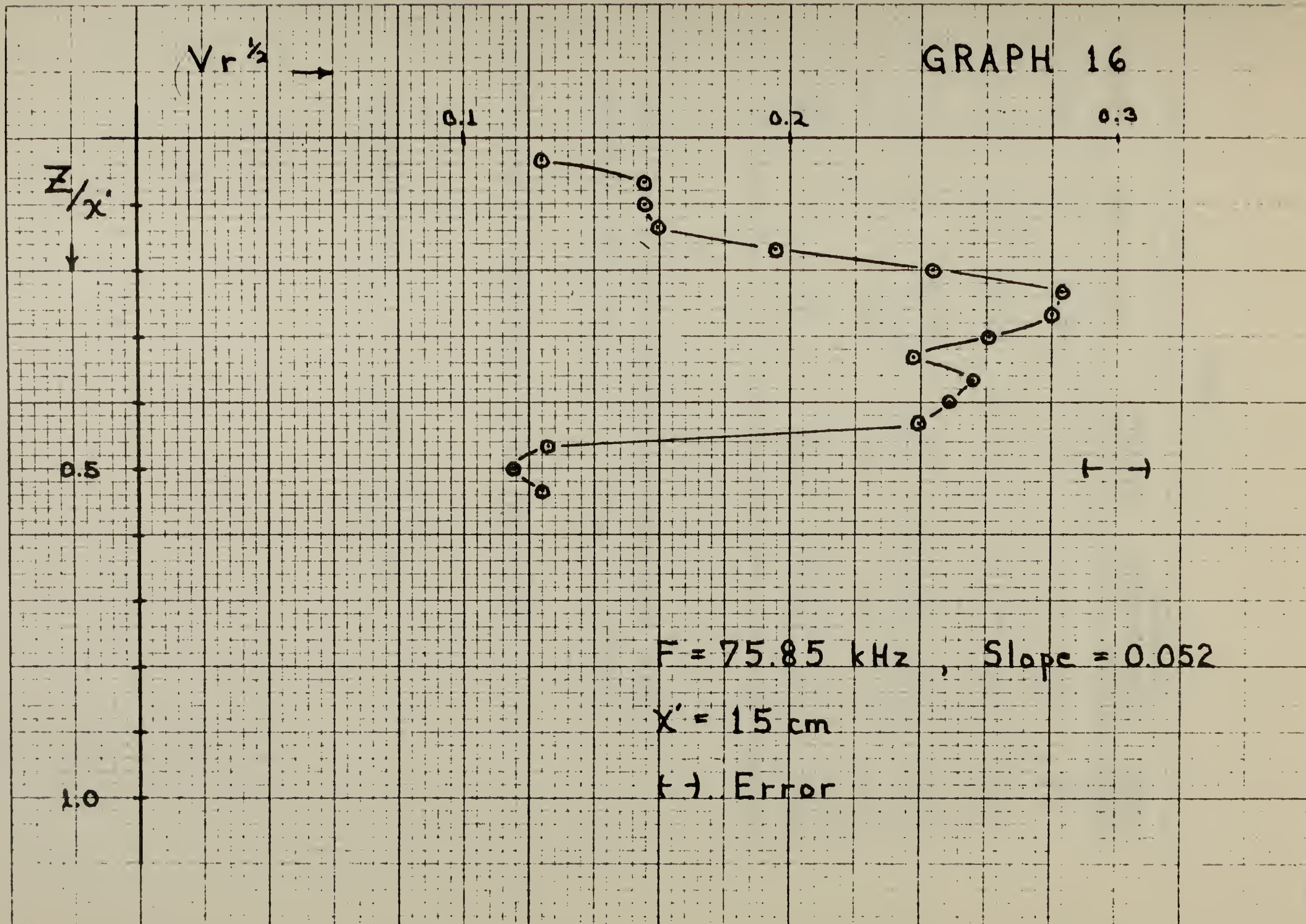
GRAPH 13
Vr½
0.1
0.2
Z/x'
0.5
1.0
F = 107.5 kHz
x' = 15 cm
Error


GRAPH 14
F = 75.85 kHz , Slope = 0.052
X' = 5 cm
⊢⊣ Error
Vr^½ →
Z/X' →
0.1
0.2
0.5
1.0





GRAPH 15
F = 75.85 kHz , Slope = 0.052
X' = 10 cm
Error
0.1
0.2
0.3
0.5
1.0
Z/X'



GRAPH 16
Vr ½
0.1
0.2
0.3
Z/x'
0.5
1.0
F = 75.85 kHz , Slope = 0.052
X' = 15 cm
⊢⊣ Error

TABLE I

F(kHz)	Mode	Slope	Estimated Beam Width	Estimated Depression Angle Method A	Method B	Related Graphs
75.85	1	0.0398	17°	11.3°	12.5°	1-4
75.85*	1	0.0398	18°	11.3°	13.3°	5,6
107.5	1	0.0398	14.4°	10.3°	11.7°	7-10
107.5	3	0.0398	16.1°	13.6°	13.7°	11-13
75.85	1	0.052	16.3°	12.2°	15.8°	14-16

Method A: Using average maximum amplitude datum.

Method B: Using bisector of average -3 dB data.

*Data from the repetition of the first stage

(Estimated errors in all angles about ±2°.)

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